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Research and Development

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Project Summary

Distributed Mixing Burner (DMB) Engineering Design for Application to Industrial and Utility Boilers

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This report summarizes the design of two prototype distributed mixing burners (DMBs) for application to industrial and utility boilers. The DMB is a low-NO_x pulverized-coal-fired burner in which: (1) mixing of the coal with combustion air is controlled to minimize NO_x emissions, and (2) an overall oxidizing environment is maintained to avoid slagging and corrosion.

Several DMB configurations were tested in two research furnaces over a range of operating conditions. The data were evaluated to develop design criteria for optimum performance. Two prototype DMBs were then designed by integrating the design criteria with commercial burner components. One burner was designed for application to an industrial size (215,000 lb/hr) Foster Wheeler boiler. The second prototype burner was designed for application to a general class of Babcock and Wilcox opposed-fired utility size boilers, because a utility size host boiler had not been selected.

This report discusses the initial prototype burner designs. Subsequent burner testing and burner design changes are discussed in other reports.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The DMB concept involves staging the combustion process to minimize NO_x emissions while maintaining an overall oxidizing atmosphere in the furnace to minimize slagging and corrosion. NO_x production from fuel nitrogen compounds is minimized by driving a majority of the compounds into the gas phase under fuel-rich conditions and providing a stoichiometry/temperature history which maximizes the decay of the evolved nitrogen compounds to N_2. Thermal NO_x production is also minimized by enthalpy loss from the fuel-rich zone which reduces peak temperatures.

Figure 1 shows schematically how the DMB design sequentially stages the fuel/air mixing. The combustion process occurs in three zones. In the first zone, pulverized coal (transported by the primary air) combines with the inner secondary air to form a very fuel-rich (20 to 50 percent theoretical air) recirculation zone which provides flame stability. The coal devolatilizes, and fuel nitrogen compounds are released to the gas phase. Outer secondary air is added in the second "burner zone" where the stoichiometry increases up to about 70 percent theoretical air. This is the optimum range for reduction of bound nitrogen compounds to N_2. Air to complete combustion process is supplied through tertiary ports located outside the burner throat. This allows substantial residence time in the burner zone for decay of bound nitrogen compounds to N_2 and radiative heat transfer to reduce peak temperatures. The tertiary ports surround the burner throat providing an overall oxidizing atmosphere and minimizing interactions between adjacent burners.

For the last several years, Energy and Environmental Research Corporation

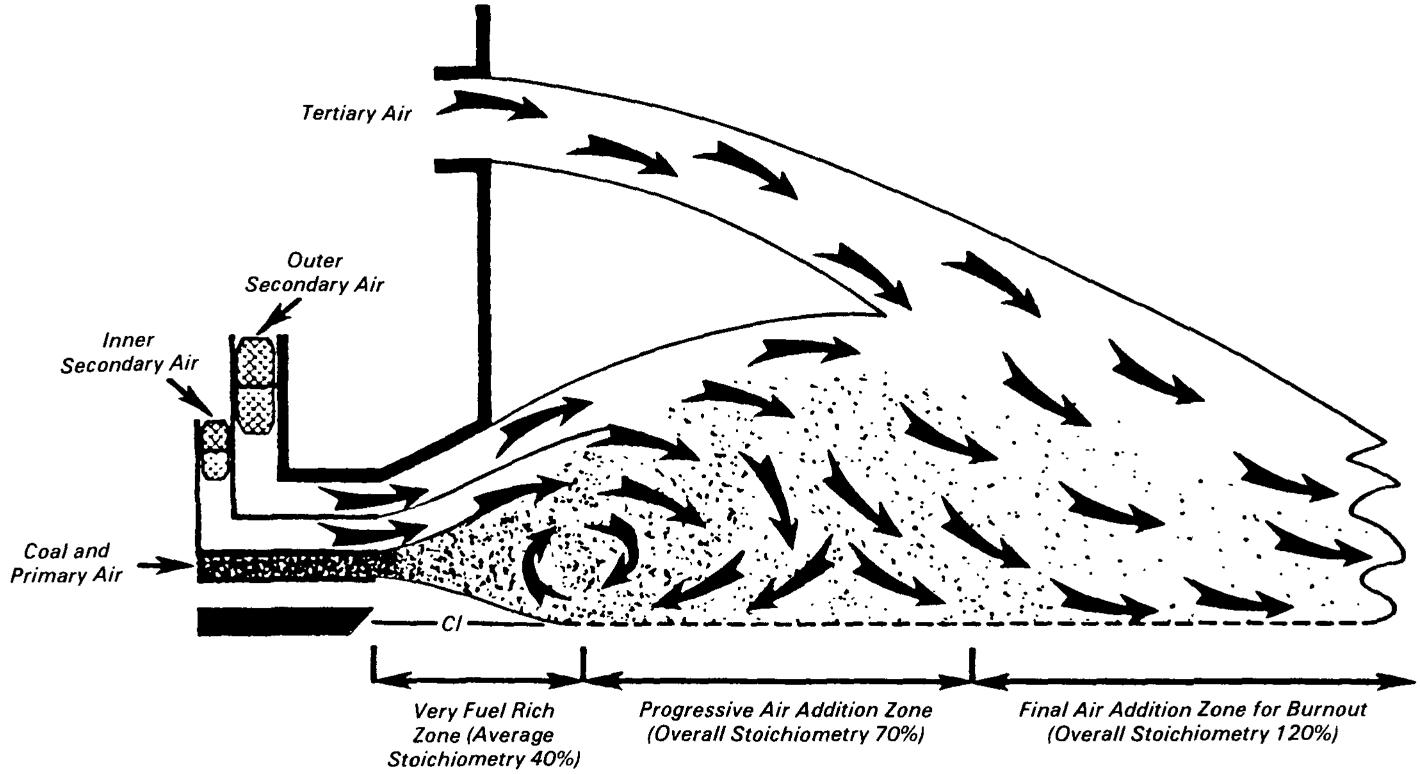

Figure 1. *DMB concept.*

(EER) has been working with the EPA to develop the DMB concept under EPA Contracts 68-02-1488 and 68-02-2667. These efforts have focused on experimentally evaluating the performance of several DMB designs in two research furnaces. Six DMBs have been tested in single- and four-burner arrays at firing rates up to 100 x 10^6 Btu/hr. The tests covered wide ranges of DMB design parameters, adjustments, and operating conditions. Under optimum conditions, NO_x levels less than 0.15 lb/10^6 Btu were achieved. However, DMB performance has not been evaluated in commercially operated steam generators.

The EPA is currently conducting two programs to provide this field evaluation. EPA Contract 68-02-3127, with EER as the prime contractor and Foster Wheeler as a major subcontractor, involves evaluation of the DMB concept on two industrial-size single-wall-fired boilers. EPA Contract 68-02-3130, with Babcock and Wilcox as the prime contractor and EER as the major subcontractor, involves evaluating the DMB concept on a utility size opposed-fired boiler. The objectives of both programs are to achieve NO_x emissions levels less than 0.2 lb/10^6 Btu without adverse effects on boiler operability and durability, thermal efficiency, and the emission of other pollutants. These field evaluations involve: (1) translation of the development burner test data into practical prototype DMBs, (2) verification of the prototype burner performance through testing in a research furnace, (3) construction and installation of these burners in the field boilers, (4) evaluation of burner/boiler performance under typical operating conditions, and (5) documentation of the results.

This report summarizes the first program element, the prototype DMBs. These burners were designed by integrating: (1) specific requirements of the host boilers, (2) DMB design criteria, and (3) commercial burner components. These burners will be tested in a research furnace to fine tune the designs and to adjust operating variables for an optimum balance between low NO_x emissions and other performance parameters. Based on this testing, the final design will be specified and the necessary burners fabricated for installation in the host boilers.

The prototype burner designs discussed in this report are these initial "flexible" designs based on the results of previous DMB development efforts and commercial burner components. During the testing of the industrial prototype burner (EPA Contract 68-02-3127) in the large watertube simulator (LWS), some design parameters were changed considerably, including incorporation of some proprietary Foster Wheeler components and parameter values. Similarly, although the utility prototype burners (EPA Contract 68-02-3130) have not yet been tested, it is expected that the final burner design may be considerably different from the initial prototype burner design included in this report. Results of this LWS testing and the changes in the burner designs are documented in annual reports for the respective programs.

Boiler Characteristics

The boiler selected as the initial industrial boiler field evaluation site is Pearl Station Unit No. 1, owned and operated by Western Illinois Power Cooperative (WIPCO), Jacksonville, IL. This unit has a maximum continuous rating of 215,000 lb/hr of steam and is single-wall-fired with four burners in a 2 x 2 array. Figure 2 is a cross-sectional view of the unit, and Table 1 lists the characteristics which impact prototype burner design.

The utility boiler demonstration site has not been selected; thus, it is not possible at this time to precisely define

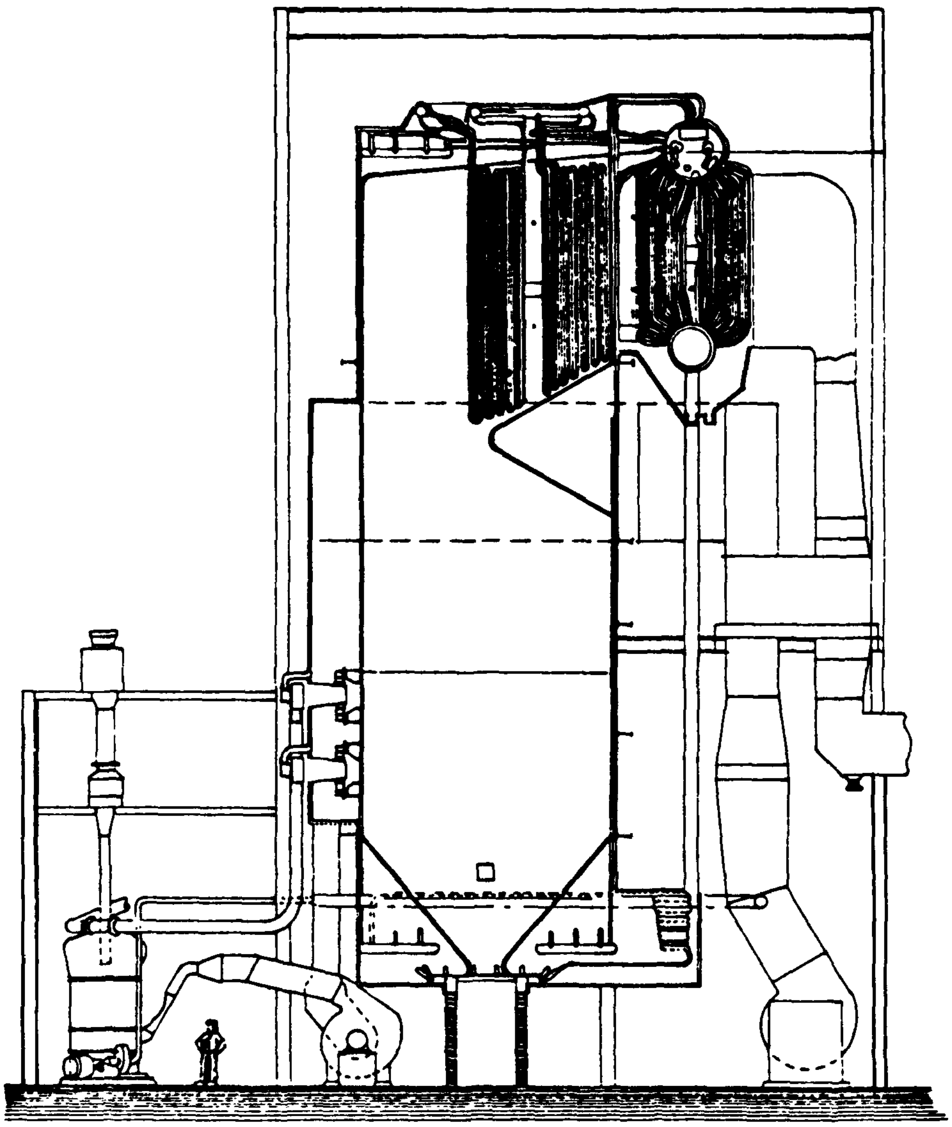

Figure 2. *Cross section of initial industrial boiler.*

the boiler characteristics which influence prototype burner design. However, the general characteristics of the family of boilers from which the field evaluation site will be selected are listed in Table 2. These characteristics were the basis for a preliminary prototype burner design.

DMB Design Criteria

Six DMB configurations ranging from 10 to 100 x 10^6 Btu/hr were tested to evaluate their potential for low NO_x emissions and to optimize their design parameters. The burners were tested in two research furnaces. A small watertube simulator (SWS), with geometry similar to a 10,000 lb/hr single-burner watertube boiler, was used to test the small burners. The larger burners (50 x 10^6 Btu/hr and larger) were tested in the large watertube simulator (LWS). This furnace has geometry similar to a large industrial or small utility boiler. It will also be used to evaluate prototype DMB performance.

The DMB tests showed that each configuration could be operated to produce stable flames and low NO_x emissions in the range of 100 ppm*. The burner parameters were found to have significant effects on burner performance. These parameters can be organized into four categories: fuel variables, secondary air variables, tertiary air variables, and exit geometry.

* All concentrations are corrected to 0% O_2, dry.

The fuel system design has significant influence on flame shape and length. Nozzles in which the coal and primary air are injected axially tend to produce slow fuel/air mixing and long diffusion flames. Nozzles with impellers cause more rapid fuel/air mixing which tends to produce shorter more compact flames. Long diffusion flames can be used in boilers with large furnace depths; e.g., opposed wall-fired units. The NO emissions from this flame type were generally lower than those for short flames. However, this may be valid only for the specific burner configurations tested and not necessarily a general result. Smaller furnaces (e.g., those in single-wall-fired units) require shorter flames to avoid flame impingement on the rear wall. The test results have shown that the short-flame DMB can be optimized for low NO emissions, but that deeper staging (low burner zone stoichiometry) is required. A DMB could be designed to vary flame shape by incorporating some mechanism for changing the spreading characteristics of the primary stream into the secondary airstream. For burners designed with annular tangential inlets, this parameter is most easily varied by burner setback which increases the residence time in the primary/secondary mixing zone upsteam of the burner throat. For burners designed with a central fuel nozzle, impeller blades can be used to increase the coal spreading rate. In the short-flame DMBs, optimum results were obtained with 45° impeller blades. However, the tests were of limited duration and did not evaluate erosion which may limit impeller life in burners operated for extended periods as in field boilers. A significant amount of data is not available to evaluate the effects of primary velocity. Consequently, DMBs should be designed to allow primary velocity to be varied during burner tuning. This could be achieved by designing for a low primary velocity and providing sleeves or other devices to reduce the nozzle exit diameter. Alternatively, a conical nozzle exit (e.g., Foster Wheeler's variable velocity nozzle) could be used.

The air system design has significant influence on NO and CO emissions. Dual secondary air channels provide additional control over fuel/air mixing rates and are thus preferred over single secondary burner designs. Burner zone stoichiometry is the major parameter controlling NO for the DMB, and the lower limit will be dictated by CO or flame stability. Flame stability can be enhanced at lower burner zone stoichiometries, however, by increasing the secondary swirl without impact on NO. Since the optimum value of swirl and

Table 1. *Initial Industrial Boiler Demonstration Site Characteristics*

Characteristic		Value
Boiler/Furnace		
Boiler Capacity, lb/hr:	*MCR*[a]	*215 x 10³*
	Peak	*245 x 10³*
Furnace Depth, ft		*20.6*
Furnace Width, ft		*16.4*
Firing Configuration		*Single Wall*
Burner Capacity, Btu/hr:	*MCR*	*69 x 10⁶*
	Peak	*80 x 10⁶*
Current Burners:	*Type*	*Intervane*
	Throat Dia., in.	*24*
Burner Array, wide x high		*2 x 2*
Burner Spacing, ft:	*Horizontal*	*6.0*
	Vertical	*6.5*
Fuel Supply System		
Coal Type		*Bituminous*
Mills:	*Type*	*Model MB*
	Number	*2*
Primary Stoichiometry at MCR, % T.A.[b]		*16*
Primary Temperature, °F		*155*
Air Supply System		
Air Heater Type		*Regenerative*
Design Point Excess Air at MCR, %		*18*
Windbox Temperature at MCR, °F		*510*
Burner Pressure Drop (nominal), in. H_2O		*3.5*
Windbox Depth, in.		*52*

[a] *Maximum continuous rating.*
[b] *Theoretical air.*

Table 2. *Approximate Utility Boiler Demonstration Site Characteristics*

Characteristic		Value
Boiler/Furnace		
Boiler Capacity at MCR[a]*, MW*		*≈350*
Furnace Depth, ft		*32-36*
Furnace Width, ft		*34-48*
Firing Configuration		*Opposed Wall*
Burner Capacity at MCR, Btu/hr		*125 x 10⁶*
Current Burners, type		*Circular or Cell*
Circular Burner Array, wide x high		*3 x 4 or 4 x 3*
Circular Burner Spacing, ft:	*Horizontal*	*8-9*
	Vertical	*8-10*
Fuel Supply System		
Primary Stoichiometry at MCR, % T.A.[b]		*25*
Primary Temperature, °F		*150*
Air Supply System		
Design Point Excess Air at MCR, %		*15*
Windbox Temperature at MCR, °F		*550*
Burner Pressure Drop (nominal), in. H_2O		*4.0*

[a] *Maximum continuous rating.*
[b] *Theoretical air.*

burner zone stoichiometry will depend on burner characteristics, swirl device, coal composition, and the overall duty cycle, DMBs should be designed with sufficient flexibility to vary this parameter. Flame stability characteristics are also influenced by the primary air velocity. The ability to vary the primary air velocity will also provide another way to operate at low burner zone stoichiometry while maintaining low CO levels. Tertiary jet velocity does not appear to be an important design parameter for NO or CO, although port location has a significant impact on CO burnout. For DMBs designed for field boilers, the location of tertiary ports will be determined in part by the burner-to-burner spacing and other furnace and windbox design parameters.

The burner exit configuration plays a key role in flame stability. For most of the DMB tests, the primary and inner secondary setbacks (distances from end of parallel throat—see Figure 3) were zero, the quarl (refractory throat divergence) half angle was 25 degrees, and its length was equal to the throat diameter. If this exit configuration is applied to DMBs for field boilers, the resulting quarl length and overall diameter will be considerably larger than current commercial practice. Consequently, a shorter quarl length will probably be required. The test results discussed above showed that flame stability decreased with quarl length, and it may be necessary to increase the coal nozzle setback or swirl on the primary or secondary airstreams to achieve satisfactory flame stability in a burner with a short quarl.

These general burner design requirements are summarized in Table 3. Several of the parameters, listed as site-dependent (S.D.), will be based on characteristics of the field boilers. It is possible that the nominal design point values may need to be varied for optimum burner performance. Thus, the prototype DMBs have been designed to be flexible so that the design parameters can be adjusted for optimum performance. Table 3 also lists the range of variables which will be examined as part of burner performance optimization tests.

Industrial Prototype Burner

Figure 3 is a cross-sectional view of the prototype burner (without tertiary air ports) showing its design details. The following Foster Wheeler commercial burner components have been used in the design: an annular coal nozzle, a telescoping coal nozzle for primary velocity control, registers for swirl control and flow shutoff, air hoods for secondary flow rate control, and a commercial flame scanning and ignition system. The coal and primary air enter through a tangential inlet to provide swirl. The coal nozzle is a tapered annulus, and the axial velocity increases as the coal and air move toward the burner throat. The exit end of the coal nozzle is formed from two concentric cones. The inner cone can be moved axially to vary the exit area, and hence, the primary velocity. The outer portion of the coal nozzle consists of removable sections so that the overall length of the coal nozzle may be changed to vary coal nozzle setback in the burner throat. Each of two concentric secondary air passages, supplied from a common windbox, has an adjustable register for swirl control, an axially movable sleeve for flow rate control, and a perforated plate (air hood) for flow rate measurement. Pressure taps on both sides of each perforated plate allows the pressure drop to be measured and correlated with sleeve positions and flow rates.

Table 3. *Distributed Mixing Burner Design Parameters*

Parameter	*Nominal Design Point*	*Testing Range*
Fuel System		
Primary Temperature, °F	*S.D.*[a]	*130-180*
Primary Stoichiometry, % T.A.[b]	*S.D.*	*17-30*
Primary Velocity, ft/sec	*75*	*50-90*
Primary Swirl	*45° Vanes*	*Variable*
Air System		
Secondary		
Temperature, °F	*S.D.*	*400-650*
Burner Zone Stoichiometry, % T.A.	*50-70*	*40-120*
Inner Swirl	*Variable*	*Variable*
Outer Swirl	*Variable*	*Variable*
Axial Velocity, ft/sec	*60*	*50-90*
Inner/Total Area	*0.33*	*Variable*
Inner/Total Flow Rate	*0.33*	*Variable*
Tertiary		
Temperature, °F	*S.D.*	*400-650*
Swirl	*None*	-
Axial Velocity, ft/sec	*50*	*40-60*
Angle, degrees	*0*	-
Number	*4*	-
Location, radius/throat diameter	*2.2*	*S.D.*
Divergence, degrees	*0*	-
Exit		
Half Angle, degrees	*25*	*Variable*
Length/Diameter	*1.0*	*S.D.*
Setback - Inner Secondary, in.	*0*	*Variable*
Setback - Outer Secondary, in.	*0*	*Variable*
Operational Variables		
Capacity, 10^6 Btu/hr	*S.D.*	-
Turndown, % capacity	*S.D.*	*≈50*
Overall Stoichiometry, % T.A.	*S.D.*	*100-150*

[a] *Site dependent.*
[b] *Theoretical air.*

The core (that portion of the burner in the coal nozzle) is supplied with a small amount of cooling air from the windbox. A retractable ignition system, including spark ignition, a 10×10^6 Btu/hr oil nozzle and a pilot flame scanner are in the core, on the burner centerline. The main flame scanner views the flame through the inner secondary air passage.

Tertiary air is supplied from the windbox through outboard tertiary air ports. The airflow rate through each port will be controlled and measured by a control valve not shown in Figure 3. Four tertiary air ports will be used for the prototype burner tests. Their locations (with respect to the burner throat) match the burner spacing in the host boiler. The port location to be used in the field will be selected to uniformly distribute the tertiary air around and between the burners. Some compromise may be required, depending on windbox construction and furnace structural considerations.

In summary, the industrial prototype burner has been designed with flexible parameters to permit the flow rates, velocities, and swirl in the burner passages to be varied to optimize burner performance. The dimensions and ranges of adjustment are listed in Table 4. All the dimensions listed match the DMB design criteria except exit length, which must be considerably shorter due to windbox depth limitations. The resulting exit-length/throat-diameter ratio is 0.40, compared to 1.0 for the DMB design point. The effects of this shorter exit length will be evaluated during the prototype tests.

Utility Boiler Prototype Burner

Since a utility host site has not been selected, a preliminary prototype burner has been designed based on the approximate utility boiler field evaluation site characteristics listed in Table 3. This burner design is preliminary in that it represents the general burner design; it does not include the flexibility inherent in the industrial prototype burner. If the industrial prototype burner test results show that additional flexibility is required in the utility prototype burner, it will be incorporated in the final design.

Figure 4 is a cross-sectional view of the preliminary utility prototype burner, showing its design details. The following Babcock and Wilcox commercial burner components were used in the burner: an axial coal nozzle, registers for flow shutoff, swirl vanes for inner secondary swirl, and a commerical flame scanning and ignition system.

The coal and primary air enter the nozzle through a 90° elbow. The inlet end of the nozzle has a venturi, designed to produce and approximately uniform distribution of coal at the nozzle exit. The two concentric secondary air passages each has a register which allows the airflow to be shut off when the burner is out of service. The outer register can be adjusted to control swirl; however, this will also vary the flow distribution among the various burner passages. The inner secondary has swirl vanes so that the inner secondary swirl is approximately independent of register position. The four tertiary air ports each has a separate damper. The tertiary ports are rectangular with the shorter dimension horizontal. This results in less disturbance to the tubewall, and hence, greater structural strength than circular ports of the same area. The oil ignitor is on the burner centerline and has a ceramic exterior to minimize wear. The scanner (not shown) views the flame through the inner secondary channel.

The dimensions of this burner are listed in Table 5. As with the industrial prototype burner, the ratios of tertiary-port-radius/throat-diameter and exit-length/diameter are less than the DMB design criteria.

Since the utility host boiler has not been selected, it is not possible to specify the furnace firing depth, and hence, the maximum acceptable flame length. Thus, is is desirable to provide some way to vary flame shape and length in the prototype burner Previous DMB tests have shown that coal nozzle design is the key parameter influencing flame shape and length. Nozzles which channel the coal into an axial jet produce long narrow flames, while nozzles which mix the coal more rapidly with the combustion air produce shorter flames. The utility prototype burner nozzle design is expected to produce a long narrow flame. During prototype burner testing, alternate nozzle designs will be evaluated so that the flame length can be tailored to match the host boiler furnace depth.

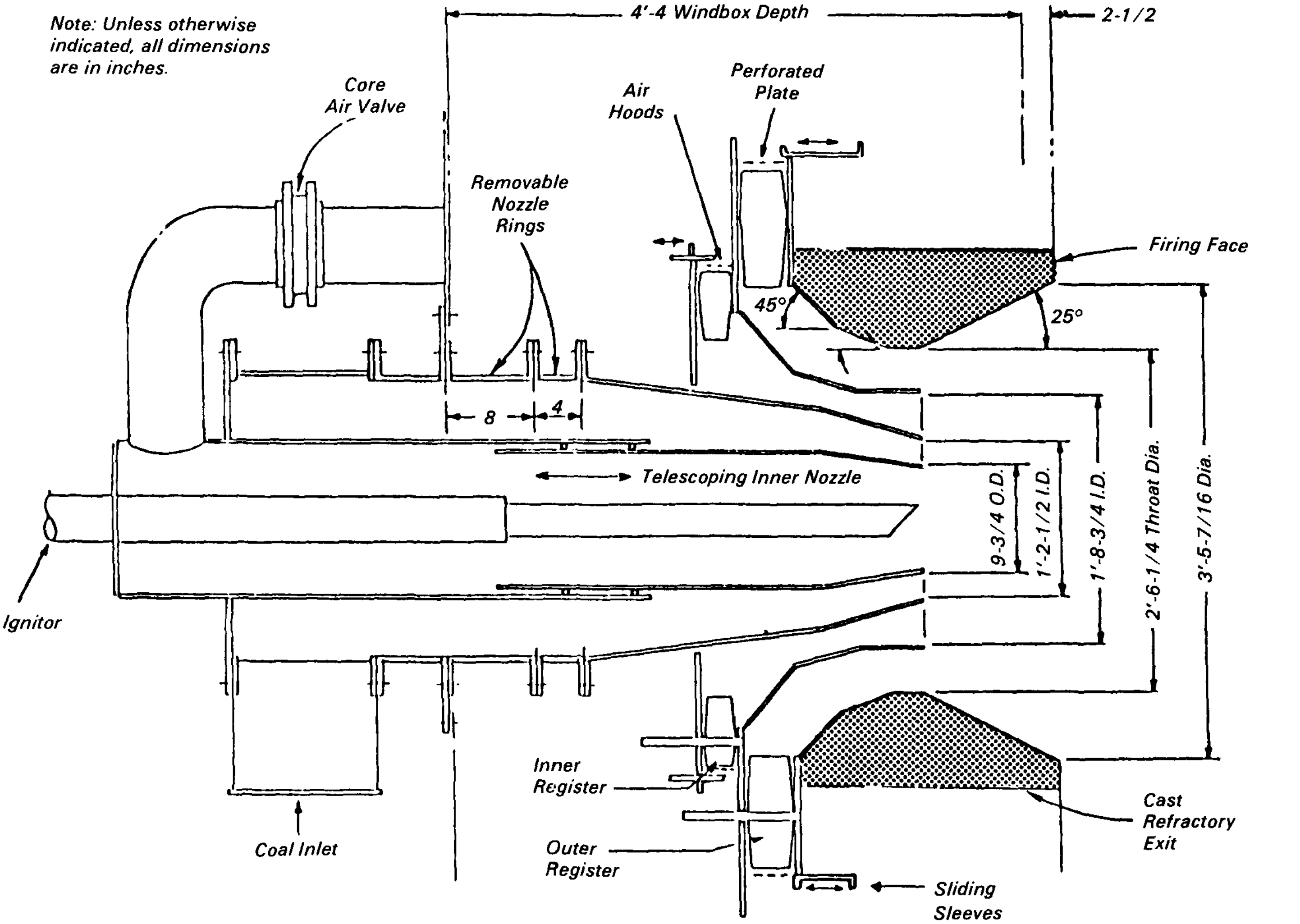

Figure 3. *Cross section of industrial prototype burner based on Foster Wheeler design without tertiary air ports.*

Prediction of Prototype Burner Field Operating Characteristics

Since the basis for the prototype design is the LWS research furnace, not a steam raising system, then some assurance is required that the DMB will perform in the field as predicted. Although indirect, the approach taken was to evaluate commercial burner operation in the LWS and compare it against field experience. This approach provides some assurance that, if the burner operates satisfactorily in the LWS, it will also operate satisfactorily in the field.

In support of the industrial demonstration program (EPA Contract 68-02-3127), a Foster Wheeler intervane burner (pre-NSPS) designed to meet the specifications of the small capacity host site boiler was evaluated over a range of excess air and load. In general, the flames produced by this burner were short, bright, intense, and stable. The base of the flame was within the cylindrical portion of the exit and filled the divergent portion. In the furnace, the flame expanded rapidly and was about 12 ft (five throat diameters) long. The burner controls (register and core air control valve) affected the flame shape: with the controls adjusted similarly to field settings, the flame shape in the LWS was somewhat narrower and longer than those observed with multiburner arrays in the field. Throughout the tests, stack opacity was low except for low excess air conditions, where some black smoke was observed. The smoke was generally light gray haze. This similarity of flame characteristics between the LWS and field intervane burner test results suggests that the short-flame DMB flame characteristcs and stability observed in the LWS will also be similar in the field.

CO emissions were about 185 ppm at 20 percent excess air. This is about a factor of four higher than typical field boiler CO levels, whch are usually less that 50 ppm. The high CO levels measured in the LWS are probably due to the relatively cold furnace design which quenches CO oxidation above the burner zone. The CO levels measured during previous DMB tests in the LWS were similar to the intervane burner levels.

NO emissions from the intervane burner, at full load and 25 percent excess air, were 500 ppm; this is about 100 ppm lower than that typically measured in field operating industrial size boilers. Foster Wheeler has found that, when two burners are tested in a research facility such as the LWS, the ratio of NO_x emissions from the same two burners operating in a commercial steam generator. Thus, the NO_x emissions from the

Table 4. Industrial Prototype Burner Dimensions and Adjustments

Design Variable	Value	Adjustment Range	Adjustment Method
Fuel Injector			
Core Diameter, in.	9.75		
Core Area, in.^{2}	74.7		
Nozzle Diameter, in.	14.5		
Annulus Thickness, in.	2.375	1.7-3.3	Telescoping
Primary Area, in.^{2}	90.5	68-136	Nozzle
Setback, in.	0	-2-+12	Remove/Replace Nozzle Rings
Inner Secondary Channel			
Outer Diameter, in.	20.75	Variable	
Annulus Thickness, in.	3.125	Variable	Replace
Area, in.^{2}	173.0	Variable	Secondary
Setback, in.	0	Variable	Divider
Outer Secondary Channel			
Outer Diameter, in.	30.25	Variable	
Annulus Thickness, in.	4.75	Variable	
Area, in.^{2}	380.5	Variable	Recast Exit
Setback, in.	0	Variable	
Tertiary Ducts			
Distance from Burner ℄, in.	53	Variable	
Spacing Around Burner, degrees	90	Variable	Modify Windbox
Number of Ports	4		
Injection Angle, degrees	0		
Axial Position, in.	0		
Diameter, in.	13.25	Variable	
Total Area, in.^{2}	553	Variable	Sleeve
Throat and Exit			
Throat Diameter, in.	30.25	Variable	
Throat Area, in.^{2}	718.7	Variable	
Half Angle of Exit, degrees	25	Variable	Recast Exit
Length of Exit, in.	12.0	Variable	
Length/Diameter	0.40	Variable	

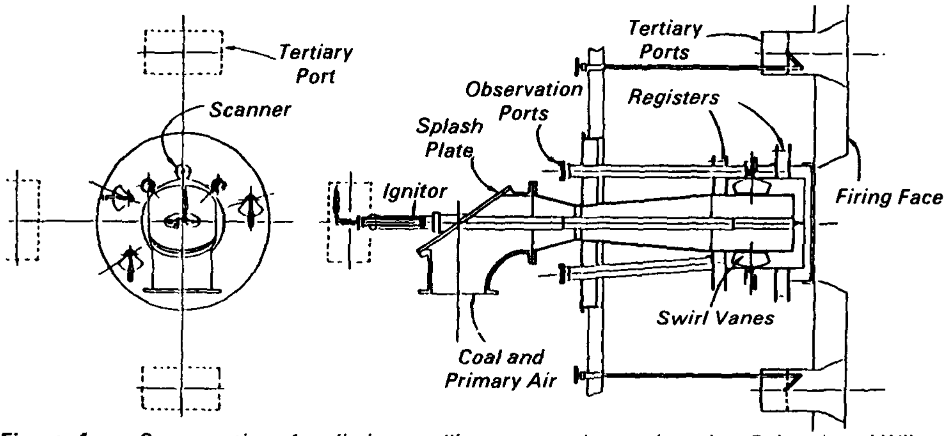

Figure 4. *Cross section of preliminary utility prototype burner based on Babcock and Wilcox design.*

DMB operating in a steam generator can be estimated from three sets of data: 1) DMB operation in the LWS, 2) commercial burner operation in the LWS, and the same commerical burner operation in a steam generator. An estimate based on the intervane burner test results is summarized below:

The predicted NO level for the DMB operation in an industrial-size steam generator (120 ppm) corresponds to 0.13 lb/10^6 Btu, which is less than the program goal of 0.2 lb/10^6 Btu. However, there is much uncertainty in this estimate: results should be used only as a rough indication of potential DMB performance in field

Burner	LWS Tests: Capacity 10^6Btu/hr	LWS Tests: NO @ 0% O_2 ppm	Field Operation: Basis	Field Operation: NO @ 0% O_2 ppm
Intervane	90	500	Typical Field Data	600
DMB	100	100	Predicted	≈120

units. A much more accurate estimate will be made by utilizing prototype DMB test data and baseline host boiler test data when available.

Conversion Factors

Readers more familiar with the metric system may use the following factors to convert the nonmetric units used in this Summary.

Nonmetric	Times	Equals Metric
Btu/hr	2.93	W_t
°F	5/9(°F-32)	°C
ft	0.305	m
in.	2.54	cm
in.^{2}	6.45	cm^2
lb	0.455	kg
lb/10^6 Btu	430	ng/J

Table 5. Preliminary Utility Prototype Burner Dimensions

Design Variable	*Nominal Value*
Fuel Injector	
Nozzle Diameter, in.	*15.25*
Primary Area, in.^{2}	*182.6*
Setback, in.	*3.0*
Inner Secondary Channel	
Outer Diameter, in.	*25.0*
Annulus Thickness, in.	*4.875*
Area, in.^{2}	*308.0*
Setback, in.	*5.0*
Outer Secondary Channel	
Outer Diameter, in.	*32.0*
Annulus Thickness, in.	*3.5*
Area, in.^{2}	*313.4*
Setback, in.	*5.0*
Tertiary Ducts	
Distance from Burner ℄, in.	*48.0*
Spacing Around Burner, degrees	*90*
Number of Ports	*4*
Axial Position, in.	*0*
Injection Angle, degrees	*0*
Length x Width, in.	*22.0 x 12.0*
Total Area, in.^{2}	*1065.0*
Throat and Exit	
Throat Diameter, in.	*32.0*
Throat Area, in.^{2}	*804.0*
Half Angle of Exit, in.	*25*
Length of Exit, in.	*7*
Length/Diameter	*0.219*

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The complete report, entitled "Distributed Mixing Burner (DMB) Engineering Design for Application to Industrial and Utility Boilers," (Order No. PB 84-163 260; Cost: $16.00, subject to change) will be available only from:

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